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SEMIANNUAL PROGRESS REPORT NO. 4
ON

MICROWAVE DEVICE INVESTIGATIONS

This report covers the period April 1, 1968 to October 1, 1968

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1. General Introduction (G. I. Haddad)

This report covers the work performed during the period April 1, 1968 to September 30, 1968. A brief description of the work performed during this period as well as the plans for the coming period are described below.

The tasks which were active during this period are:

a. Relativistic Electron-Beam Devices for Millimeter-Wave Generation:

The work on this phase of the program has been discontinued due to the many difficulties that were encountered. These are described in a later section of this report.

b. Beam-Plasma Interaction for Amplification and Harmonic Generation:

The work on this phase of the program is described in more detail in later sections of this report. Considerable progress has been made and two reports summarizing this work by Messrs. G. T. Konrad and J. D. Gillanders are presently being prepared. It is anticipated that this phase of the program will be completed by January, 1969.

c. Electron-Beam Cyclotron Instabilities for Harmonic Generation:

The corkscrew magnetic field arrangement for producing transverse velocities in an electron beam has been tested and preliminary results indicate that it is working properly. Further tests are planned. The complete system will be constructed during the coming period. This work will be continued during the coming year.

d. Millimeter- and Submillimeter-Wave Detectors: Preliminary experimental results have been obtained on the paramagnetic downconverter. These are encouraging and a detailed evaluation of the various properties of this detector are presently underway. This work will be continued during the coming year.

Some of the new tasks which will be initiated during the coming period are:

1. Investigation of the possibility of converting the Cerenkov radiation equipment into an ion-implantation machine.
2. Investigation of superconducting junctions for millimeter- and submillimeter-wave detection.
3. Investigation of high-frequency limitations of avalanche diodes including tunneling effects which become prominent at high frequencies.

2. Experiments on a Relativistic Electron-Beam Device

Supervisor: J. E. Rowe

Staff: G. T. Konrad

2.1 Introduction. The object of this experiment has been to obtain Cerenkov radiation in the 2 mm wavelength region by passing a tightly bunched relativistic electron beam through a dielectric material. A bunching frequency of 7.5 GHz was used, while the output frequency of the device was to be 150 GHz. This is the 20th harmonic of the bunching frequency. In order to obtain Cerenkov radiation under these conditions, the bunched beam has to be accelerated to voltages in the vicinity of 400 to 600 kV and then passed through a quartz cone mounted within an elliptic cavity. The reason for using such a high voltage is that a tightly bunched relativistic electron

beam is rich in harmonics. By using a depressed potential beam collector a considerable portion of the high d-c beam power employed can be recovered.

2.2 Description of the Experimental Apparatus. The gun used in this experiment was a conventional, convergent, solid-beam gun operating at voltages as high as 100 kV. At this voltage the beam current was designed to be 0.1 A with a cathode current density of 0.5 A/cm^2 and a final beam diameter of less than 2 mm.

The electron beam produced in this gun was injected into the buncher, which consisted of an extended interaction circuit of the standing-wave type using a coupled-cavity circuit. The individual cavities of the circuit were stacked inside a thin-wall stainless steel cylinder, which was water-cooled from the outside. The gun and buncher, which were self-aligning with each other, were mounted to the vacuum chamber containing the high-voltage bushing in such a way that final adjustments in the alignment could be made while the device was operating.

The bunched beam was injected into the vacuum chamber, in the center of which was mounted the high-voltage anode. This anode contained an elliptic cavity which served as the Cerenkov coupler. The cavity was a right elliptical cylinder, with dimensions much larger than a wavelength. Along one focus of the elliptical cylinder the bunched electron beam was allowed to pass in a direction parallel to the axis of the cylinder. The dielectric material in the vicinity of the beam was a quartz cone, which had a relatively low loss tangent and excellent vacuum properties. The remainder of the cavity was filled with a dielectric material of $\epsilon_r \cong 20$. The shape of the quartz cone was determined in part by the characteristics of this artificial dielectric and in part by the operating voltage of the device. A long-wire

antenna was located at the other focus of the elliptic cylinder. This antenna was coupled into a cylindrical waveguide which gradually opened up into a horn. Appropriate lenses were used to transmit the 150 GHz radiation to the collector flange, where a similar horn and waveguide arrangement were located.

The electron beam collector at the far end of the vacuum chamber made use of a magnetic field perpendicular to the electron motion. This field deflected the electrons so that they could be collected on water-cooled V-shaped copper plates. The magnetic field also kept the secondary electrons generated in the collector from returning to the vacuum chamber. This was of considerable importance because the device was operated with the collector at ground potential, which means that the collector was at a greatly depressed potential compared to the high-voltage anode.

2.3 Operation of the Device. Initially the beam transmission to the collector was checked while the high-voltage anode was not in the chamber. Thermal velocities were found to have a pronounced effect in broadening the beam. Calculations indicated that the beam transmission through the gun anode (which was 0.080 inch in diameter) should vary between 10 percent at 1 kV, 43 percent at 10 kV and 98 percent at 100 kV. These figures could be quite closely substantiated experimentally, at least for lower voltages. With the high-voltage anode in place, these results were not markedly different, but the critical alignment requirements posed problems to be described below. As the voltage was increased above 20 or 30 kV, the beam interception was high enough, even though it was decreasing with voltage, to cause considerable heating of the gun anode and buncher. The beam power levels were sufficiently high so as to liberate large amounts of gas and to vaporize the metal in the

areas where the beam was striking. This caused the pressure in the gun to rise, and the cathode emission consequently dropped. By the time a voltage of 70 to 80 kV could be attained, the beam current had fallen off to a fraction of its design value.

The beam was very difficult to focus into the high-voltage anode hole due to alignment problems. The buncher, anode and collector were carefully aligned with a laser beam. For some operating voltages the beam appeared to strike the anode hole exactly on center and some transmission to the collector was observed. This transmission fluctuated between 0 and 90 percent. Evidently this erratic behavior was due to charging up of the quartz cone by intercepted beam electrons. This situation was improved with a conductive copper coating along the hole in the cone, but was not eliminated.

In changing the operating voltage from a value optimized for good beam transmission to a different value the collector current was usually lost entirely. To obtain transmission again it was necessary to move the buncher mechanically and realign all field coils individually. (There were seven coils for producing an axial focusing field of 200 to 300 G). While this alignment procedure was being performed, the beam would strike the sides of the anode hole, vaporizing metal, and the vacuum in the chamber would deteriorate.

The beam apparently did not go through the chamber in a straight line. Even though the magnetic field, when optimized, varied at most 5 percent throughout the region of interest, there was a sufficiently large radial field component present to cause the beam to spiral. The earth's magnetic field and the presence of large magnetic objects, such as power supplies,

in the vicinity of the chamber can also be expected to perturb the focusing field slightly. Since the distance through the device from gun to collector was in the order of one meter, these extraneous magnetic field components caused a substantial electron deflection.

Initially a mercury diffusion pump was used to maintain a vacuum of approximately 1×10^{-6} Torr in the chamber. Under these conditions the high voltage bushing, with the anode attached, could hold off approximately 300 kV, provided that no axial magnetic field was present. When a field of only a few tens of gauss was present, a continuous discharge would take place in the chamber. Since the operating magnetic field was 200 to 300 G, this was one of the major problems. By replacing the diffusion pump with an ion pump a pressure of 2×10^{-8} Torr could be maintained in the chamber. Even though a voltage of several hundred kV could be applied to the anode for certain values of magnetic field, this was still not satisfactory. Since the magnetic field had to be adjusted in order to optimize beam transmission, breakdown usually occurred for voltages slightly below 100 kV.

2.4 Conclusions. In attempting to operate the relativistic electron-beam device three major problems were encountered. These were:

- a. Poor beam transmission due to thermal effects,
- b. Alignment problems with the various components and
- c. High-voltage breakdown.

Even though each one of these problem areas was improved appreciably in a series of experiments, it was not possible to operate the device at a power and voltage level high enough to observe any output in the millimeter wave region. In view of the fact that further major changes in the device would be required, it was decided to discontinue the work on this experiment.

3. Beam-Plasma Interactions

Supervisor: R. J. Lomax

Staff: J. D. Gillanders

The great interest in electron-beam plasma interactions in recent years has been stimulated by the possible applications in several fields of endeavor. Nuclear scientists are interested in a method of plasma heating for thermonuclear reactions. Microwave engineers are interested in amplification and generation of signals, and space physicists are interested in understanding the phenomena of the upper atmosphere and solar radiations.

The presence of gain or an instability can be determined by examining the dispersion equation of the interaction. Simplified theories which ignore collisions, finite temperatures and some or all of the boundary conditions predict gains and instabilities much stronger than observed experimentally. In the simplest cases infinite gains are predicted. However, when the above factors are not ignored the dispersion equation becomes much more complicated. Therefore, a very efficient method is needed to solve the equation if information about the interactions is to be obtained in a reasonable amount of computation time. The method now being used on the IBM 360/67 is several times more efficient than the method used previously on the IBM 7090. In addition the new computer is faster and more efficient.

The old method using Runge-Kutte integration to trace the roots $k(\omega)$ of the dispersion equation $D(\omega, k) = 0$ for the beam-plasma system was much more efficient than the searching methods of finding the roots previously used by most people. This method required the derivatives of the function to be evaluated four times for each new point. In addition it was necessary to evaluate the function and its derivatives several times in order to use

Newton's method to correct the errors that accumulated after several steps of integration. On the average the dispersion function and its derivatives had to be evaluated five or six times for each new point found.

The new method uses low-order prediction formulas to get the first four points and then a four-point predictor formula using the four previous points and the derivatives at these points to predict each new point. At each new point the function and its derivatives are calculated and Newton's method is used to correct the point. Usually, after the first few points have been found it is only necessary to evaluate the function and its derivative once to obtain each new point to the desired accuracy. This is considerably faster than the previous method.

This new method has been programmed for the IBM 360/67 and checked out. A Calcomp plotter has recently become available on the system and this will be used to plot the roots of the dispersion equations for study.

The results obtained to date indicate both convective and absolute instabilities as shown by previous work for the simplified cases. Preliminary results including collisions show the heavy damping of these instabilities as expected for high collision frequencies. However, for very low, but nonzero collision frequencies there appears to be a singularity either in the equation or the numerical method. This will be studied further in the future.

Considerably more information will be available once the results from the program are plotted. This is being done at the present time.

4. The Study of Cyclotron Harmonic Instabilities

Supervisor: W. D. Getty

Staff: A. Singh

The objective of this part of the project is the study of instabilities in a magnetized plasma with an anisotropic velocity distribution:

$$f(v) = \frac{1}{2\pi v_{\perp 0}} \delta(v_{\perp} - v_{\perp 0}) \delta(v_{\parallel} - v_{\parallel 0}) ,$$

where v_{\perp} and v_{\parallel} refer to velocities perpendicular and parallel to the magnetic field.

As a first step in the solution of the boundary value problem stated in the last report,¹ we have derived the dielectric tensor for the medium. The work on the solution of the boundary-value problem will be continued.

As part of the experiment proposed in the last report, a tube with an electron gun and Wingerson-type corkscrew was built and is being tested on an electron beam analyzer. The preliminary results obtained are in agreement with the theory. The corkscrew was designed to give an axial-to-transverse velocity conversion ratio of 0.4 at a beam voltage of $V_0 = 576.0$ V and at a magnetic induction of $B_0 = 180$ G. It has been observed that the corkscrew operates satisfactorily at other beam voltages and axial magnetic field strengths provided $\sqrt{V_0/B_0}$ is maintained constant. Under these conditions the fraction of axial velocity that is converted to transverse velocity is determined by the magnitude of the dc current carried by the corkscrew.

1. Haddad, G. I. et al., "Frequency Multiplication in High-Energy Electron Beams," Semiannual Progress Report No. 3, Grant No. NGR 23-005-183, Electron Physics Laboratory, The University of Michigan, Ann Arbor; April, 1968.

The tests on the gun-corkscrew system will be continued to get more information about the behavior of the corkscrew and the velocity distribution of the beam. The tube proposed in the last report will then be assembled to carry out the microwave tests.

5. Harmonic Generation in a Beam-Plasma System

Supervisor: J. E. Rowe

Staff: G. T. Konrad

This portion of the program concerns itself with the study of harmonic generation and coupling schemes in beam-plasma systems. The theoretical aspect of the work consists of the derivation and solution of nonlinear large-signal equations describing beam-plasma interactions, including higher harmonic RF components. The plasma column is regarded as a transmission line with lumped circuit components, which can be determined in terms of the various plasma parameters. Thus, the one- and two-dimensional large-signal analyses for conventional traveling-wave amplifiers are directly applicable with only minor modifications.

A large number of computer runs have been obtained for both the one- and the two-dimensional model. The saturation characteristics and the amplitudes of the fundamental as well as the harmonic RF currents are available for each case. Collision effects were also included in the one-dimensional case. For a typical beam-plasma amplifier the collisions between beam electrons and the plasma particles reduce the gain and the harmonic current levels by several dB, while collisions among the plasma particles are shown to have a minor effect.

A large amount of gain and harmonic data was obtained on the experimental device. Due to the high coupling loss of the coupled helix couplers no net gain was recorded, but the electronic gain was in the range of 20 to 35 dB.

In some instances the second harmonic power level came to within 5 dB of the fundamental. Most of the results were in quite good agreement with the theoretical calculations.

A coupling loss of 10 to 15 dB per coupler could be achieved with the elliptic cavity couplers. Unfortunately this required a sufficiently high pressure in the system (above $1 \cdot 10^{-2}$ Torr) so that the double-ended FIG discharge could be used. Under these conditions the pressure in the beam gun region was too high for good electron emission. Thus the advantages of the elliptic cavity couplers could not be fully realized in the present device. It is believed that a differently designed device could operate in a higher pressure region. In such a case a considerable amount of net gain should be obtainable with the cavity couplers.

The work on this phase of the program is essentially completed. A technical report describing the results in detail is in preparation.

6. Paramagnetic Materials for Millimeter- and Submillimeter-Wave Detection

Supervisor: G. I. Haddad

Staff: C. F. Krumm

The purpose of this phase of the program is to investigate the feasibility of using paramagnetic materials to detect millimeter- and submillimeter-wave radiation. The downconversion scheme which is currently being studied is similar in principle to a three-level maser. Two signals, one a millimeter-wave frequency and the other a microwave frequency are partially absorbed by the material. The power reflected at the microwave frequency depends upon the power incident at the millimeter-wave frequency. Monitoring the changes in reflected microwave power corresponds to detection of the millimeter-wave signal.

The device which was built for testing the detection scheme has recently been operated successfully at liquid helium temperatures. Preliminary results indicate a minimum overall conversion loss of approximately 25 dB. This includes all line losses and mismatch losses at both the millimeter and microwave frequencies. This conversion loss decreases linearly with increasing microwave power level. The loss of -25 dBm was observed when the incident power level was -20 dBm. The limitation in this respect was boiling of the helium at high input power levels.

The lowest power level detected on these initial experiments was -35 dBm. The apparent limitation here was a lack of sensitivity in the microwave detector. It is hoped that this figure can be significantly decreased by using a microwave superheterodyne receiver in future experiments.

Further experiments will be performed with the downconverter shortly in an effort to definitely establish some of the following properties:

1. Dynamic range,
2. Response time,
3. Internal conversion loss,
4. Input and output mismatch losses and
5. Noise properties.

When these experiments have been completed the results obtained will be compared with those derived theoretically.

Comparison between the initial results and the derived equivalent circuit indicates satisfactory agreement.

7. Bulk Semiconductor Materials for Millimeter- and Submillimeter-Wave Detectors

Supervisor: G. I. Haddad

Staff: I. I. Eldumiaty

The main purpose of this phase of the program is to investigate bulk semiconductor materials for millimeter- and submillimeter-wave detection. The proposed detection scheme was described in the previous report.

In order to determine the characteristics of the detection scheme, a detailed and thorough evaluation of the properties of suitable materials is required. This will be done at millimeter and microwave frequencies in the presence of both dc electric and magnetic fields.

At the present time theoretical and experimental investigations are being carried out to develop an equivalent circuit for the bulk material in a reentrant cavity. Also, the change in conductivity of the semiconductor material at low temperature is being studied theoretically as a function of the electric and magnetic field parameters.

Some modifications on the experimental apparatus have been made; spring contacts for the InSb samples have been provided. These will be used to provide dc bias to the sample and at the same time will prevent them from cracking in the process of cooling to cryogenic temperatures.

In the next period the theoretical investigation of the change in the conductivity will be continued and cavity perturbation techniques will be used to verify the results; in addition the characteristics and limiting factors of the detection scheme will be studied.